MATERIALS PROCESSING

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ADAPTIVE CONTROL OF DIAMOND DRILLING OF NONMETALLIC MATERIALS

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The basic principles for selecting the work regimes for diamond drilling of nonmetallic materials are presented. The process of microcutting by a single diamond grain is examined, and relations between the components of the cutting force and the ratio of the rate of the main motion to the feed rate are obtained on the basis of known relationships. It is shown that adaptive control of the drilling nonmetallic materials is possible using two-circuit systems — one for feed-rate control and one for cutting-rate.

The advancement of modern machine and instrument building is dependent on the development and adoption of progressive technological processes for working new materials. The wide range of requirements imposed on the output parameters of manufactured articles makes it necessary to use in industry materials which have high mechanical, physical, and chemical characteristics (durability, minimal friction, heat resistance, minimal CLTE, corrosion resistance, antimagnetism, and others). Brittle nonmetallic materials, such as glass, ceramic, and sitals (glassceramics), meet these requirements to a large extent. They are finding increasingly wider applications in machine building, electric technology, instrument building, chemical sectors of industry, aerospace and rocket technology, and nuclear power.

One of the most labor-intensive operations in working nonmetallic materials is shaping openings. There are several methods for making openings in parts made of such materials. These methods all have a number of technological limitations, due to the limitations on the nominal size of the openings being made (electron-beam shaping, laser shaping), ecological hazards, and high tool wear (ultrasonic shaping), on applications and on the type of material being worked. Thus, diamond drilling is one of the most effective methods for working openings with diameters ranging from 0.8 to 1000 mm and larger [1].

Diamond drilling is identical to the process of cutting-in by grinding with a circular face, but this process is used under special, extreme, conditions of grinding because there is full contact between the cutting surface and the part being worked and because debris is not automatically removed from the work zone.

It has been determined that the production rate of diamond drilling has an extremum corresponding to the drill operating in the self-sharpening regime. Thus, the optimal work regimes will correspond to the diamond drill operating in the self-sharpening regime, which will decrease the number of corrections made to the tool, stabilize the process of dispersing material, and yield the maximum possible production rate for prescribed properties of the material and tool.

The diamond drilling process is characterized by a large number of factors and is often unstable because of changes occurring in the physical-mechanical properties of the material being drilled, tool wear, deformations in the machining system, and others. Consequently, the use of automatic control systems will optimize the conditions during the entire machining time.

The method of mechanical working that optimizes the process by changing the work condition, first and foremost, the cutting regimes, depending on the specific work conditions in real-time, is called adaptive cutting.

An adaptive system for stabilizing the cutting force by changing the feed so as to maintain the maximum production rate of the diamond drilling process with a prescribed quality of the surface of the parts being machined was developed in [2]. This made it possible to solve the problem of automatic drilling of the substrates of microcircuits made of glass, glassceramic, and polychore and to increase the production rate by a factor of 1.3 with the required surface quality.

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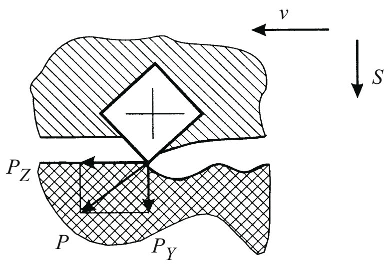

Fig. 1. Forces acting in the grain – bonding and grain – part systems.

At the present time the cutting rate for diamond drilling is set according to the recommendations of diamond-drill manufacturers, and the change in the optimal ratio of the feeding to cutting rates is not taken into account in the drilling process. For example, the recommended cutting rate is 1 – 2 m/sec for diamond drills on "MonAliT" bonding and 0.5 – 5 m/sec for drills on other types of bonding. Under these conditions it is best to use a two-circuit system to stabilize the cutting rate and force for automatic selection of cutting regimes and adaptive control of these regimes.

To develop such a system it is necessary to analyze the effect of the cutting rate v on the main parameters of the diamond drilling process and to prove the possibility of adaptive control of this process.

Let us examine the forces acting in the grain – bonding and grain – part systems (see Fig. 1) during microcutting of a nonmetallic material by a single diamond grain in the diamond drilling process.

It has been established [1] that for optimal dispersing of brittle nonmetallic materials for a single grain there exist relations between the axial component of the cutting force $P_Y^{\text{s.g}}$ and the tangential component $P_Z^{\text{s.g}}$ of the cutting force. They can be approximated by a relation of the form

$$P_Z^{\text{s.g}} = a + bP_Y^{\text{s.g}},$$

where the coefficient a is small and $b = 0.12 \pm 0.048$ for the principal nonmetallic building materials, such as, glass, ceramic, and glassceramic.

Examining the work performed by a group of grains, i.e., the diamond drill as a whole, having measured the macroparameter P_Y and knowing the geometric dimensions of the drill, the concentration of diamonds, and the granularity of the diamond powder, the following relation can be used to estimate the axial component of the cutting force on a single grain [1]:

$$P_Y = P_Y^{\text{s.g}} m = P_Y^{\text{s.g}} \times 0.00369 \frac{(D^2 - d^2)C}{G^2},$$

where P_Y is the axial component of the cutting force, N; $P_Y^{\text{s.g}}$ is the axial component of the cutting force of a single grain, N; m is the number of cutting diamond grains on the tip of the drill; D and d are the outer and inner diameters of the drill, respectively, mm; C is the relative concentration of diamonds, %; G is the weighted-mean diameter of a grain, µm.

In diamond drilling, not all grains present on the tip of the tool participate in the cutting process. Therefore, to estimate $P_Y^{\text{s.g}}$ more accurately m should be replaced with m^{r} — the real number of cutting grains on the drill tip, which can be determined using known empirical relations [1].

In the drilling process, the tangential component P_Z of the cutting force together with friction forces creates a torque, to overcome which the main drive of the machine tool applies a torque to the spindle. Thus, the torque on the spindle can be measured and $P_Z^{\text{s.g}}$ can be estimated from the relation

$$M_{\text{tor}} = P_Z^{\text{s.g}} \times 0.00145 \frac{(D^2 - d^2)CD}{G^2},$$

where M_{tor} is the torque, N · mm, and $P_Z^{\text{s.g}}$ is the tangential component of the cutting force of a single grain, N.

According to the theory of similarity [3], two physical phenomena are similar if the numerical values of all quantities characterizing the first phenomenon in one system can be obtained in another system by multiplying the corresponding quantities by certain factors, called scaling factors.

Let us assume, on the basis of dimensional analysis and geometric considerations, that the ratio P_Z/P_Y is similar to the ratio v/S. Indeed, the vectors comprising this ratio are pair-wise collinear and in the absence of rotation of the drill the tangential component P_Z is 0 and in the absence of feeding S the axial component of the cutting force $P_Y = 0$ (in a steady regime, i.e., no seizing).

Thus, the proof of the similarity of the ratio P_Z/P_Y to the ratio v/S reduces to finding the scaling factors [3, 4].

The relations for the torque during drilling of industrial glass with 12 – 25 mm in diameter tubular drills are

$$M_{\text{tor}} = 4.0654 P_Y^{1.66} D^{2.7} A^{-0.4}, \quad (1)$$

for natural diamonds and

$$M_{\text{tor}} = 0.73681 P_Y^{1.67} D^{2.5} A^{-0.12},$$

for drills with synthetic ACB diamonds; here, M_{tor} is the torque, N · m, and A is the grain size of the diamonds ($A = 16$, 20, 25, i.e., grain-size designation according to GOST 9206–80).

The relation between the per minute feed S and the number n of revolutions of the drill has the form

$$S = 0.06 \times 10^{-3} hmkn, \quad (2)$$

where h is the average penetration depth of a single grain into the material being machined, m, and the coefficient k takes account of the overlapping of the grains.

Using the well-known relation (2)

$$n = v\,\frac{60}{\pi D}\,, \quad (3)$$

where v is the tangential velocity of the drill (cutting rate), m/sec, and substituting the expression (3) into Eq. (2) we obtain

$$S = 0.06 \times 10^{-3}\,hmkn\,\frac{60}{\pi D}\,. \quad (4)$$

Rewriting Eq. (3) we obtain D:

$$D = 0.0036hmk\,\frac{v}{S}\,\frac{1}{\pi}\,. \quad (5)$$

Neglecting friction, we shall assume that the torque on the spindle of the machine tool equals the torque produced by the tangential component of the cutting force and that the drilling process is steady. Then, the expression (1) can be written in the form

$$P_Z\,D/2 = 4.0654P_Y^{1.66}D^{2.7}A^{-0.4}. \quad (6)$$

Using the expression (6), we determine the tangential component of the cutting force as

$$P_Z = 8.1308P_Y^{1.66}D^{1.7}A^{-0.4}. \quad (7)$$

Substituting the expression (5) into Eq. (7), we write the expanded relation for determining P_Z:

$$P_Z = 8.1308P_Y^{1.66}[0.0036hmk\,(v/S)(1/\pi)]^{1.7}A^{-0.4}$$

and simple manipulations yield

$$P_Z/P_Y = 5.699 \cdot 10^{-4}P_Y^{0.66}[hmk\,(1/\pi)]^{1.7}(v/S)^{1.7}A^{-0.4}, \quad (8)$$

which can be written as

$$P_Z/P_Y = f_1(P_Y)[v/S]^{1.7}. \quad (9)$$

The expression (9) is characteristic for a nonlinear correspondence, which is a particular case of an affine-functional correspondence. The phenomena (processes) under real conditions and in the model are affine-functional if they can be approximated by different equations and a functional relation between their similar quantities can be established in terms of the affine connectedness of continuous groups of transformations, reducing the initial equations to an identical dimensionless form. In general, the scaling factor is not constant but rather a function f [3, 4].

Similar manipulations give an expression for the ratio of the tangential to the axial components of the cutting force using drills with ACB grade diamonds:

$$P_Z/P_Y = 3.183 \times 10^{-4}P_Y^{0.67}[hmk\,(1/\pi)]^{1.5}(v/S)^{1.5}A^{-0.12}. \quad (10)$$

This can also be put into the form

$$P_Z/P_Y = f_2(P_Y)[v/S]^{1.5}.$$

The relations (8) and (10) contain separate empirical dependences and need further analysis and experimental refinement in order to extend them to a wider range of drill diameters and diamond-powder grades. These expressions also confirm that the diamond drilling process can be controlled not only by controlling the fee, as in existing systems [1], but also by controlling the cutting rate.

The transformed relations (8) and (10) taken together with the method for calculating the optimal axial force [1] can be used to select diamond drilling regimes with deterministic control of the machining process (manual or programmed).

Maintaining the optimal ratio P_Z/P_Y can be used to maximize the volume of material destroyed by the diamond drill in two-circuit (via feed and cutting rate) systems of automatic control of the diamond drilling process of machine tools with numerical control. To develop an adaptive system of a high-quality regulator it is necessary to solve the problem of two-parameter optimization of a model of the diamond drilling process taking account of the requirements imposed on the surface quality of the part being machined.

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